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ABSTRACT

The problem of calculating the radiation dose in earth orbit produced by energetic electrons and their associated bremsstrahlung is considered. Two methods of electron dose calculation are described, and areas where improvement could be made in either input data or calculational techniques are pointed out. It is concluded that bremsstrahlung calculations are sufficiently accurate for present purposes but that additional Monte Carlo calculations of electron penetration of thick shields (thickness greater than 70% of the electron range) are needed for accurate electron dose calculations.

For the 250 nautical mile orbit phase of Apollo Mission E, present calculations predict an electron dose of 2.2 rad/day in the lunar module and .012 rad/day in the command module. This assumes the predicted decay rate of the artificially injected Starfish electrons is correct. These doses are approximately a factor of two higher than results obtained with earlier Monte Carlo transmission data. Comparison with estimated proton skin doses of .20 rad/day and .07 rad/day for the LM and CM respectively indicates that electrons will be the major contributor to skin dose in the lunar module. Electron bremsstrahlung is not a problem at these flux levels.

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FROM: J.S. Ingley

TECHNICAL MEMORANDUM

I. INTRODUCTION

The problem of radiation shielding in space can be divided into three catagories: 1. Shielding against heavy charged particles, mainly protons; 2. Shielding against electrons; 3. Shielding against secondary radiation (e.g. bremsstrahlung) produced by energetic electrons and protons. The relative importance of these radiation sources in determining the radiation dose depends on the spacecraft's location in space and the amount of shielding available. Outside of the Earth's trapped radiation belts solar flare and solar wind protons and alpha particles are the predominant radiation sources. In the radiation belt environment both protons and electrons can contribute to the dose, with the electron contribution becoming relatively less important as the shielding thickness increases. For Apollo Mission E electrons contribute over 90% of the skin dose in the LM and only 15% in the CM. Secondary bremsstrahlung, being much more penetrating than the primary charged particles, sets a lower limit on the shielded radiation dose. In this study the problem of calculating radiation dose due to energetic electrons and their associated bremsstrahlung is considered. Therefore, the results will be particularly applicable to space flights in the Earth's radiation belts in relatively thin-walled spacecraft such as the lunar module. However, it should be kept in mind that proton doses, which are not considered here, can be an appreciable if not predominant factor in many cases. Rather than produce an entirely new electron dose code, the purpose of this study is to investigate various methods of electron dose calculation in order to point up possible areas where improvement could be made in either input data or calculational techniques.

Electron dose calculations are complicated by the fact that the analytic solutions to the problem of electron transport in matter are not possible without drastic simplifying assumptions.[1] As a result Monte Carlo techniques have been extensively developed as a means of approaching the problem. However, because of the great amount of computer time needed for a sophisticated Monte Carlo code to solve a given problem, it is not possible for large scale radiation dose studies to be done in this

manner. What is done, therefore, is to generate solutions for simple geometries and a limited number of materials using Monte Carlo techniques, and then generalize the results so that they can be used to calculate the dose for more complicated geometries. In this way a variety of shielding configurations and external electron environments can be studied for a minimum investment in computer time.

The most extensive set of Monte Carlo electron transport calculations have been carried out by Berger and Seltzer. Their code has been described in detail elsewhere[2] and will not be discussed here. Their results give the fraction of incident electrons of initial kinetic energy, E, penetrating an aluminum slab of thickness z (gm/cm^2)* as a function of the reduced thickness, $x = \frac{z}{R_o(E)}$, where $R_o(E)$ is the extrapolated range of the incident electrons in aluminum. Tables of number transmission coefficients are given for various incident electron energies and angles, and for isotropic ($dN(\theta) = N_o \cos\theta d\theta$) incidence. In addition tables of energy transmission coefficients are also given; i.e., the fraction of incident energy that is transmitted though a slab of reduced thickness x. Recently Berger and Seltzer have also calculated the fraction of incident electron energy that appears as forward bremsstrahlung from aluminum slabs of varying thicknesses.[3] These results can be used to calculate the bremsstrahlung contribution to the electron dose.

In the next section methods of calculating the primary electron dose are described, and the limitations of the calculations are discussed in section III. Section IV is concerned with the calculation of the bremsstrahlung dose. Section V contains dose calculations for Apollo Mission E and compares these results with previous work. Section VI summarizes the results of this study and makes recommendations for further study in this area. The appendix contains a complete description of the code, BEDOSE, which was used to do the calculations, including input-output format and a listing.

II. ELECTRON DOSE

Consider a semi-infinite aluminum slab of thickness z (gm/cm^2) irradiated on one face by an isotropic electron flux $\phi(E,t)$ whose time integrated value is $\Phi(E)$ (electrons/cm^2-MeV)(see Figure 1). The electron number and energy transmission coefficients of Berger and Seltzer are defined as follows:

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*$z(g/cm^2) = \rho(g/cm^3) \times t(cm)$ is called the areal density and is the quantity usually used to describe shielding thicknesses. Ranges expressed in this unit for a given particle vary much less from one material to another than if expressed in centimeters.

$$T_N(E_o,z) = \frac{\text{\# of electrons of initial energy } E_o \text{ penetrating slab}}{\text{\# of electrons of energy } E_o \text{ incident on slab}}$$

$$T_E(E_o,z) = \frac{\text{total energy of electrons of initial energy } E_o \text{ that penetrates slab}}{\text{total energy incident on slab due to electrons of initial energy } E_o}$$

These coefficients can be used in two ways to calculate the electron dose delivered to a material on the shielded side of the slab.

Using the number transmission coefficient, the number of electrons of initial energy E penetrating the slab per cm^2 is simply $\Phi(E)\, T_N(E,z)dE$. The skin dose in rads produced by these electrons will be

$$dD_e(z) = 1.6 \times 10^{-8} \frac{\overline{dE'}}{dz} \Phi(E)\, T_N(E,z)dE. \qquad (1)$$

$\frac{\overline{dE'}}{dz}$ is the average energy per unit depth (MeV/gm/cm^2) deposited by the electrons of initial energy E after penetrating the slab, where the averaging is done over the emergent electron spectrum. The constant 1.6×10^{-8} converts from (MeV/gm/cm^2) to rads (100 ergs/gm). Since electrons in the trapped radiation belts have a wide spectrum of energies equation (1) must be integrated over energy to obtain the total electron dose,

$$D_e(z) = 1.6 \times 10^{-8} \int_0^\infty \Phi(E)\, T_N(E,z) \frac{\overline{dE'}}{dz}(E,z)dE \qquad (2)$$

$\Phi(E)$ can be obtained from models of the space electron environment and T_N from Berger's work. $\frac{\overline{dE'}}{dz}$ is a little more difficult. It is not simply calculated from the absolute value of the stopping power of the material in question for two reasons. The electrons do not travel in straight paths and they enter the material at a variety of angles. Therefore, the actual distance traveled by the electrons is greater than their depth of penetration. Calculations with $T_E(E,z)$ (the next method to be discussed) show that $\frac{\overline{dE'}}{dz}$ is actually 2-3 times times the absolute value of the stopping power. However, these calculations also show that $\frac{\overline{dE'}}{dz}$ is a fairly insensitive function of E and z, as might be expected from the insensitivity of the stopping power to variations in energy between 0.5 and 10 MeV.[4] Therefore, we can replace $\frac{\overline{dE'}}{dz}$ by an average value $\langle \frac{dE'}{dz} \rangle$ to give us

$$D_e(z) = 1.6 \times 10^{-8} \langle \frac{dE'}{dz} \rangle \int_0^\infty \Phi(E)\, T_N(E,z)dE. \qquad (2a)$$

Because of the considerable amount of computer time required to obtain values of the number coefficient, values at more than a few energies have only recently become available. It turns out that if z is replaced by the reduced width $x = x/R_o$, the values of $T_N(E,x)$ are fairly insensitive to variations in E. This enables one to use a universal function $T_N(x)$ in place of $T_N(E,z)$ in equation (2a). In the past $T_N(x)$ has been constructed from Monte Carlo runs using 1 MeV incident energy electrons, giving the dose equation.

$$D_e(z) = 1.6 \times 10^{-8} \left\langle \frac{dE'}{dz} \right\rangle \int_0^\infty \Phi(E)\, T_N(1,x)\, dE \,. \qquad (2b)$$

In actual practice upper and lower limits are set on the energy range of integration, above which there is assumed to be a negligible number of electrons and below which it is assumed no electrons penetrate the slab. We will come back to this point and the question of using a universal transmission function after developing the second method of electron dose calculation.

The second method of calculating the electron dose makes use of the energy transmission coefficients of Berger and Seltzer. It was first brought to this writer's attention in a paper (unpublished) by M. Burrell and J. Wright of MSFC,[7] although the arguments advanced here differ from theirs in certain respects. We will assume for the present that we have a universal energy transmission curve $T_E(x)$. Consider the effect of increasing the slab thickness from x to $x+\Delta x$. The quantity $T_E(x+\Delta x)-T_E(x)$ will be equal to the fraction of the incident energy deposited in $\Delta z = R_o \Delta x$. In making this argument we tactily assume that the fraction of energy reflected backward is negligible or more appropriately that in the limit of vanishingly small Δz this reflected energy is compensated for by backscattered energy from material farther on. Therefore, the dose delivered to Δz is

$$D_{\Delta z} = \frac{1.6 \times 10^{-8} (T_E(x+\Delta x) - T_E(x))}{R_o(E)\, \Delta x} \Phi(E) E\, dE$$

where $R_o(E)\, \Delta x = \Delta z$. For skin or surface dose in any material on the shielded side of the aluminum slab we let $\Delta x \to 0$ and integrate over E to obtain

$$D_e(z) = 1.6 \times 10^{-8} \int_0^{\infty} \Phi(E)\, E\, \frac{dT_E(x)}{dx}\, \frac{1}{R_o'(E)}\, dE, \qquad (3)$$

where we have replaced $R_o(E)$ by $R_o'(E)$, the electron range for the material in question, and $x = \frac{z}{R_o(E)}$ is the reduced thickness for the aluminum slab. $\Phi(E)$ can be obtained from models of the space electron environment, $\frac{dT_E(x)}{dx}$ can be calculated from the transmission data of Berger and Seltzer, and $R_o(E)$ and $R_o'(E)$ can be obtained from the range-energy tables of Berger and Seltzer.[4] Equation (3) can be used to calculate the dose directly, whereas in equation (2b) it was necessary to estimate $\langle \frac{dE'}{dz} \rangle$. In fact equation (3) will later be used to determine $\langle \frac{dE'}{dz} \rangle$ for various spectra and slab thicknesses. As before, limits must be put on the integral in equation (3) in order to numerically integrate it. The calculations indicated in equations (2b) and (3) are carried out by the code BEDOSE (Bremsstrahlung-Electron Dose). This code is described in detail in the appendix including input and output formats and a listing of the program. Since it is to be expected that any radiation dose code intended for space applications will be used for a wide variety of environmental conditions, it is necessary to clearly understand the limitations of such a code in order to correctly interpret the results. In the next section the electron dose calculation described above is examined in detail.

III. LIMITATIONS

To properly apply equations (3) or (2b) to the calculation of electron doses in space, it is necessary to understand both the limitations of the calculations and the limitations of the inputs which go into the calculations. In this section the following problems will be discussed:

1. The variation of the transmission curves with incident electron energy.
2. Lack of transmission data for values of x between 0.7 and 1.
3. Choice of a low energy cutoff for the integration.

4. Lack of electron spectral data at high energy.

5. Choice of a high energy cutoff for the integration.

Problems 2 and 3 and problems 4 and 5 are of course related.

In order to illustrate various problems discussed below, two sample electron spectra will be used in equation (2b) or (3); a so called soft spectrum represented by

$$\Phi(E) = 2e^{-2E} \ (MeV^{-1})$$

and a hard or fission spectrum (taken from Reference 8) given by

$$\Phi(E) = 0.71e^{-.575E - .055E^2} \ (MeV^{-1}).$$

Both spectra are normalized so that $\int_0^\infty \Phi(E)dE = 1$ and are shown in Figure 1a. The latter spectrum is typical of regions in the trapped radiation belts where electrons from the Starfish high altitude nuclear explosions still predominate while the former is more typical of the natural electron environment in earth orbit.

Recent calculations indicate that the transmission curves cannot be considered to be independent of energy, especially for values of the reduced thickness greater than 0.5. Figure 2 shows the number transmission curves for 1 MeV and 6 MeV electrons isotropically incident on an aluminum slab. These curves are taken from Monte Carlo calculations of Berger and Seltzer.[3] If a significant fraction of a particular electron dose is due to electrons that have penetrated a reduced thickness greater than about 0.5, the result of the calculation will depend on which curve is used. Figures 3a and 3b show the variation of the energy and number transmission coefficients with energy for various values of the reduced thickness. A good fit to this energy variation can be obtained with the following formulas:

$$T_E(E,x) = T_E(2,x)\left(\frac{E}{2}\right)^{0.91 \ln \frac{T_E(6,x)}{T_E(2,x)}} \quad 1 \leq E \leq 6 \ MeV, \tag{4}$$

$$T_N(E,x) = T_N(2,x)\left(\frac{E}{2}\right)^{0.91 \ln \frac{T_N(6,x)}{T_N(2,x)}} \quad 1 \leq E \leq 6 \ MeV. \tag{5}$$

For E <1 MeV or E>6 MeV one should use the 1 MeV and 6 MeV transmission curves respectively.

Table I illustrates the effect of the variation in the two transmission curves. Electron dose in aluminum is listed versus slab thickness for the hard and soft electron spectra. The calculations have been normalized to give a dose of one rad with the 1 MeV transmission curves at each shield thickness. $T_E(6,x)$ and $T_E(1,x)$ were used in equation (3) to obtain the numbers in Table I. The difference in dose produced by the two transmission curves increases with shield thickness and is greater for the soft spectrum than the hard spectrum. This is to be expected since for thicker shields and/or softer spectra, the electrons contributing to the dose will have penetrated greater reduced thicknesses, and the variation in the transmission curves increases with increasing x. The dose calculations in Section V use $T_E(6,x)$ and $T_N(6,x)$ since these curves give the most conservative answers.

As can be seen in Figure 2, the transmission coefficients have been calculated only for $x \leq 0.7$. This is due in part to the fact that large amounts of computer time are needed to obtain statistical accuracy for thick slabs. Although energy and number transmission coefficients are quite small for higher values of x, this region may be the main contributor to the dose for electron spectra that decrease rapidly with energy. Figure 4 shows $T_E(6,x)$ for isotropically incident electrons, and compares it to the analytic fit to the calculations used in equation (3). The minimum energy cutoff used in the integration in equation (3) will determine how far the transmission curve must be extrapolated. Figures 5a and 5b are histograms of the contributions to the electron dose as a function of the incident electron energy for the 2.0 and 4.0 gm/cm^2 slabs in Table I. The minimum energy for the integration was chosen so that $x \leq 1.0$. The histogram area is normalized to unity, and results for both the hard and soft electron spectra are shown. The energy points at which x = 0.7 and 1.0 are marked by arrows.

It is easily seen that a significant portion of the dose is due to electrons that have penetrated reduced thicknesses greater than 0.7. Furthermore this percentage increases with shield thickness and spectrum softness. For the case of the soft spectra incident on the 4.0 gm/cm^2 slab over 95% of the dose is produced by electrons for which x is greater than 0.7, and for the 2.0 gm/cm^2 slab over 50% of the dose is produced in this manner.

SHIELD THICKNESS (gm/cm^2)	SOFT SPECTRUM		HARD SPECTRUM	
	T(6,x)	T(1,x)	T(6,x)	T(1,x)
0.5	1.2 RAD	1 RAD	1.1 RAD	1 RAD
2.0	1.7 RAD	1 RAD	1.5 RAD	1 RAD
4.0	2.4 RAD	1 RAD	2.1 RAD	1 RAD

TABLE I

EFFECT OF TRANSMISSION CURVE VARIATION ON DOSE

It is not unlikely that the extrapolation in Figure 4 could be off by as much as a factor of 10 at x =1. Monte Carlo calculations at x = 0.8, 0.9 are necessary for dose calculations in situations where thick shields are required.

Figures 5a and 5b also illustrate another point that must be considered in the dose calculation. As the slab thickness increases and/or the spectrum hardens, the dose contribution comes from increasingly higher energy electrons. The maximum energy cut-off used in the integral of equation (3) was 10 MeV for the graphs in Figures 5a and 5b. However, for the 4.0 gm/cm^2 slab contributions from electrons with E>10 MeV would not be negligible ($\sim$ 10% for the hard spectrum). Measurements of electron spectra in space have not been made in this energy range. All that is usually available is an integral measurement above 4 or 5 MeV and these are limited in number. The spectrum shape below this value is then extrapolated out to higher energies. This is a further source of possible errors in the calculations if the actual spectral shape encountered differs considerably from the extrapolated shape.

The use of a 6 MeV transmission curve in cases where most of the dose contribution is coming from electrons of 7 MeV or more, such as the 4.0 gm/cm^2 slab, is a further uncertainty. Transmission calculations for 10 MeV incident electrons are needed for dose calculations involving high energy electrons.

It has been shown in this section that the calculation of electron dose can involve the use of data which has been extrapolated a considerable distance from either measured of calculated values. This is true of both the electron spectral shape and the electron transmission coefficients. In the next section the calculation of the secondary electron bremsstrahlung dose is undertaken and shown to be in reasonably good shape.

IV. BREMSSTRAHLUNG DOSE

Berger and Seltzer have also calculated the forward bremsstrahlung* efficiency for electrons isotropically incident on aluminum slabs. This is the fraction of incident electron energy that appears as forward directed bremsstrahlung on the shielded side of the slab. They express this fraction as

$$Y = 10^{-4}\, a(z,E)ZE, \qquad (6)$$

where Z is the atomic number (13 in the case of aluminum), E the kinetic energy of the incident electrons, and Y is the forward bremsstrahlung efficiency. When expressed this way, "a" is a slowly varying function of E and z (the slab thickness) having a nominal value of about 4. Two graphs of Y vs z/R_o for different values of E (Reference (3)) are shown in Figure 6.

*Bremsstrahlung, or "braking radiation" consists of electromagnetic radiation (x-rays) with energies up to that of the electron producing it, which is produced in the slowing down of the energetic electrons.

Using equation (6) the bremsstrahlung energy flux emerging from the slab is given by

$$F_b(z) = \int_0^\infty 10^{-4} \; Z \; \Phi(E) \; a(z,E)E^2 \; dE \; (MeV/cm^2), \quad (7)$$

The bremsstrahlung dose for material adjacent to the slab is simply $[1.6 \times 10^{-8} \; \langle\sigma_a\rangle \; F_b(z)]$ where $\langle\sigma_a\rangle$ is the mass absorption coefficient for the material in question averaged of the emerging bremsstrahlung energy spectrum. For the bremsstrahlung energies encountered in space applications $\langle\sigma_a\rangle$ for tissue is approximately .031 cm^2/gm, and the dose is given by

$$D_b(z) = 6.45 \times 10^{-13} \int_0^\infty \Phi(E)E^2 \; a(x,E)dE, \quad (8)$$

where we have replaced a(z,E) by a(x,E), making it a function of the reduced thickness to agree with the tabulated data in Reference (3). An analytic fit to Berger and Seltzer's tabulations of a(x,E) gives

$$a(x,E) = 44 \; e^{-\frac{.125E^{.321}(x-0.6).}{R_o(E)}} \qquad x \geq 0.6, \quad (9a)$$

$$a(x,E) = 24.3 \times ^{1.13} e^{-1.88x} \qquad x<0.6, \quad (9b)$$

where $R_o(E)$ is again the electron range in aluminum and $x = \frac{z}{R_o}$. Limits on the integration are not critical for equation (8) because the behavior of the integral is determined by the $\Phi(E)E^2$ term which is sharply peaked at an energy $E = \frac{2}{b}$ for a spectral shape e^{-bE}.

A graph of bremsstrahlung dosevversus slab thickness is shown in Figure 7 for the hard and soft electron spectra. The code BEDOSE using equations (8), (9a) and (9b) was used to do the calculation. The doses have been normalized to one electron per cm^2 striking the slab. A histogram of dose contributions versus electron energy for the hard spectrum incident on a 4.0 gm/cm^2 slab is presented in Figure 8. The dotted line is a plot of $\Phi(E)E^2$. The deviation at low energies is due to the decrease in a (x,E) at low energy because of absorption of the low energy bremsstrahlung in the aluminum slab.

Although the values of a(x,E) used in equation (8) strictly apply only to bremsstrahlung from aluminum slabs, estimates for bremsstrahlung doses from other materials can be obtained simply by scaling equation (8) by $\frac{Z}{13}$, the atomic number ratio.

As shown above the electron bremsstrahlung calculation is a straightforward procedure and does not require extrapolation of Monte Carlo or spectral data to any great degree. As a result, estimates of bremsstrahlung dose produced by primary electrons is of sufficient accuracy for any anticipated space applications.

V. APOLLO RADIATION DOSES

The calculation of radiation dose for a specific mission requires combining the mission profile with a suitable model of the space radiation environment to produce an average omnidirectional electron flux environment for the spacecraft. Although the electron flux at various points in space can be highly directional, the assumption is usually made that random orientation of the spacecraft produces an average flux that is isotropically incident on the spacecraft. Vette et al have calculated average omnidirectional fluxes for a variety of circular orbits at inclination from 0 to 90° based on their model AE2 electron environment.(5) This environment is constructed from experimental measurements made in the 1962-64 time period. Orbital fluxes for a projected December 1968 electron environment based on observed time decay of the fluxes from the Starfish nuclear detonation have also been calculated.

Figure 9 shows the average electron flux spectrum which would be encountered in a 300 nautical mile altitude, 30° inclination circular orbit. Both the 1964 flux and the projected December 1968 flux are shown. The softening of the spectrum between 1964 and 1968 is due to decay of the Starfish electrons.

Part of the mission profile for Apollo Mission E calls for a 250 nautical mile earth orbit for up to two weeks with extended occupation of the lunar module (LM). Since the spectral shape is independent of altitude in this region, the 300 nautical mile fluxes may be used to calculate dose in the command module (CM) and the LM, and the results scaled to the 250 nautical mile altitude. Figure 10 is a plot of the electron flux above 0.5 MeV versus altitude for 30° inclination circular orbits. The fluxes are taken from reference (5). The 250 nautical mile flux is 0.41 of the 300 nautical mile flux for both the 1964 and predicted 1968 data.

The differential spectra given by Vette extend from 0 to 7 MeV with an integral value given for the total number of electrons above 7 MeV. In carrying out the dose calculations these electrons were handled in two ways. One set of calculations was carried out with the differential spectrum decreasing exponentially:

$$\int_7^\infty \Phi(7)e^{-a(E-7)}\,dE = \text{number of electrons above 7 MeV.}$$

A second set of calculations was carried out with the differential spectrum assumed to be constant out to a value E_{max} and zero thereafter so that

$$\Phi(7)[E_{Max} - 7] = \text{number of electrons above 7 MeV.}$$

These two cases are shown by the dotted lines in Figure 9 and represent hard and soft extremes of spectral behavior. For the shield thickness of interest, the differences in dose were less than 10%. The more conservative (i.e. higher dose) exponential spectrum was used for the doses presented here. It should be pointed out that all spectral behavior above 4 MeV is based on extrapolation even though integral numbers may be available experimentally.

The electron and bremsstrahlung doses as a function of slab thickness are shown in Figure 11 for the 1964, and projected 1968 spectra. The doses are normalized to one electron per cm^2 striking the slab. In order to apply these results to a spacecraft geometry the following line of reasoning is used The electron dose received by an astronaut will be a skin dose because of the limited penetrating ability of the electrons. The astronaut's body will shield his skin from all electron radiation except that coming from in front of the area under consideration. The maximum skin dose will be produced over that area of the astronaut's body that faces the thinnest part of the spacecraft. The maximum skin dose that can be produced by the electrons in a spacecraft geometry can therefore be obtained from the slab results of Figure 11 using a slab thickness corresponding to the thinnest portion of the spacecraft. If the astronaut is moving about so that different parts of his body face the thin portions of the spacecraft at different times, then the total skin dose received by any portion of his body will be less than the maximum possible values calculated here.

The dose curves in Figure 11 are normalized to one electron/cm^2 striking the slab (i.e., spacecraft), and the dose values given must therefore be multiplied by the number of electrons per cm^2 striking the spacecraft in order to obtain the electron dose. If we consider the electron flux to be isotropic, the number of electrons per cm^2 striking the spacecraft's surface will be equal to 1/4 of the omnidirectional flux, or $\frac{\Phi}{4}$ (see e.g., Reference (9)).

For the penetrating bremsstrahlung radiation, the entire spacecraft will contribute to the dose. Moreover, the dose will be essentially a whole body dose since little attenuation is provided by the astronaut's body. Considering the spacecraft as a thin spherical shell, the bremsstrahlung dose is given to a good approximation by the slab results with an incident flux on the slab of $\frac{\Phi}{2}$ or $\frac{1}{2}$ the omnidirectional flux.

Doses for the CM and LM are given in Table II for 1964 and 1968 electron fluxes. The 300 n.mi. results have been multiplied by 0.41 to convert them to a 250 n.mi. orbit. A minimum thickness of 2.5 gms/cm^2 and 0.2 gms/cm^2 were assumed for the CM and LM respectively in determining the maximum electron dose. The bremstrahlung dose assumed average aluminum thicknesses of 5 and 1 gm/cm^2 for the CM and LM respectively. Also listed in Table II are the values of $\left\langle \frac{dE'}{dz} \right\rangle$ required to make equation (2b) agree with equation (3). The straight ahead value (i.e., the value

TABLE II

ELECTRON AND BREMSSTRAHLUNG DOSE FOR APOLLO MISSION E

	Electron Spectra	Electron Dose (rad/day)	Brems-strahlung Dose (rad/day)	$\left\langle \frac{dE'}{dz} \right\rangle$ (MeV/gm/cm^2)
Command Module	1964	.10	.0072	5.7
	1968	.012	.0002	5.0
Lunar Module	1964	59 (59)	.018	5.1
	1968	2.2 (1.7)	.0003	5.0

assuming the electrons to be undeflected) for tissue is $\sim$2 MeV/gm/cm^2. The actual energy deposition is therefore about 2.5 times the straight ahead value for perpendicularly incident electrons.

The LM electron dose is produced by electrons in the range 0.5-3 MeV while the CM dose is produced by electrons greater than 5 MeV. This is shown in Figures 12 and 13 where the energy contributions to the dose are plotted for the 1964 and 1968 spectra respectively. Table III lists percentages of dose from electrons with $x \geq 0.7$ and from electrons with $E \geq 7$ MeV.

TABLE III

PERCENTAGE OF ELECTRON DOSE CONTRIBUTION FROM VARIOUS REGIONS OF x,E SPACE

		$x \geq 0.7$	$E \geq 7$ MeV
CM	1964	35%	30%
	1968	5%	85%
LM	1964	1%	0%
	1968	25%	5%

Only the 1968 CM electron dose has a major portion contributed by electrons in the (x>.7,E>7 MeV) region, but the calculated dose is low enough that fairly large errors in the electron spectrum can be tolerated.

Since low energy electrons produce the LM dose, dose calculations were repeated using $T_E(1,x)$ in place of $T_E(6,x)$. These numbers are given in parentheses in Table II. No change was observed for the 1964 LM dose as should be expected from the fact that the (x>.7) portion of the transmission curve contributes little to the dose. The 1968 LM dose was reduced by 23% due to the fact that 25% of the dose comes from the ($x \geq 0.7$) portion of the transmission curve.

The electron doses in Table II are in general a factor of 2-3 higher than similar calculations using transmission coefficients available prior to reference (3). Table IV lists electron doses for the CM and LM calculated using the 1 MeV transmission coefficients from Reference (6). The Monte Carlo code used to calculate these coefficients did not include energy loss straggling, and the coefficients are too small for

large values of x. The degree of difference between the old and new doses is directly related to percentage of the dose contributed by electrons with large values of x.

TABLE IV

ELECTRON DOSES USING OLD TRANSMISSION COEFFICIENTS

		Dose (rad/day)	Dose Ratio (Table II/Table IV)
CM	1964	.031	3.2
	1968	.008	1.5
LM	1964	45	1.3
	1968	1.0	2.2

In order to assess the relative importance of the electron dose calculation to the overall question of radiation dose determination, it is necessary to estimate the magnitude of the proton dose. Using the proton fluxes in Reference (10) and the proton transport calculations of Reference (11), the skin dose due to protons is estimated to be approximately .070 rad/day for the CM (compared to .012 rad/day from electrons) and .20 rad/day for the LM (compared to 2.2 rad/day from electrons). The proton doses are in approximate agreement with calculations of R.H. Hilberg Reference (12). Thus electrons contribute over 90% of the skin dose in the LM and 15% in the CM using the 1968 electron environment. If the 1964 electron environment is used, the electron contribution to skin dose in the CM increases to 60%.

The critical phase of Apollo Mission E, for radiation dose is the occupation of the LM. Although the predicted 1968 dose is within the allowable limits, the 1964 dose is not. More up to date measurements of the electron environment would certainly be of great value in verifying the factor of 30 decrease in dose that is predicted from decay of the high energy Starfish electrons. CM doses are low enough that no hazard should result either from errors in radiation environment prediction or electron penetration calculations. Bremsstrahlung is not a problem at these flux levels and shield thicknesses.

VI. SUMMARY

The problem of determining electron radiation dose in spacecraft has been investigated in detail and several areas of weakness in the calculations have been found. Of particular

concern, is the lack of transmission coefficient calculations for shield thickness nearly equal to the extrapolated electron range, and lack of electron spectral information above 4 or 5 MeV. This information would be needed to calculate electron dose behind the moderately thick shields required for high altitude orbiting laboratories. In addition, the increase in the transmission coefficients with incident electron energy was shown to increase significantly the calculated dose over that obtained with the old 1 MeV transmission curves. Electron bremsstrahlung dose calculations were also studied. The accuracy of this rather straightforward calculation is sufficient for radiation dose predictions.

Radiation dose calculations for the 250 n. mi. orbit phase of Apollo Mission E showed the LM electron dose estimates to be within acceptable levels if the 1964 to 1968 electron flux decay is as predicted. Since the 1964 dose would not have been within acceptable limits, it would be wise to measure at least partially the 1968 environment prior to Apollo Mission E. Bremsstrahlung dose was not a problem at these flux levels.

1011-JSI-bl

J.S. Ingley

Attachments
Appendix A
Listing and sample output for code BEDOSE
Figures 1 through 13

REFERENCES

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APPENDIX

Computer Code BEDOSE

I. GENERAL DESCRIPTION

BEDOSE (Bremsstrahlung-Electron Dose) calculates the radiation dose delivered to the surface of a slab of material shielded by various thicknesses of aluminum slabs from electrons of varying energy incident on the slab. It is patterned after a similar code developed at MSFC (Reference (7)). Both the dose due to electrons that penetrate the slab and bremsstrahlung from the electron slowing down process are included in the calculation. In order to calculate the dose, the code makes use of electron transmission coefficients and bremsstrahlung efficiency coefficients previously calculated by much more involved Monte Carlo procedures. The electron dose in rads is calculated by numerical integration of the following equation:

$$D_e(z) = A_k \int_{E_{min}}^{E_{max}} E\,\Phi(E)\,\frac{dT_E(E,x)}{dx}\,\frac{dE}{R_o'(E)} \cdot \qquad (A1)$$

$\Phi(E)$ is the differential flux of electrons of energy E incident on the slab per cm^2 ($MeV^{-1}cm^{-2}$).

$T_E(E,x)$ is the fraction of the incident electron energy flux, $E\Phi(E)dE$, that is transmitted through a reduced thickness, x (determined from Monte Carlo calculations).

x is the reduced thickness, $\frac{z}{R_o(E)}$.

z is the slab thickness in gm/cm^2

$R_o(E)$ is the extrapolated range (gm/cm^2) in aluminum of electrons of incident energy E.

$R_o'(E)$ is the corresponding range in the material being irradiated (e.g., tissue).

E_{max} is the upper energy cutoff in MeV above which it is assumed no electrons contribute to the dose.

E_{min} is the lower energy cutoff in MeV below which all electrons are assumed to be stopped in the slab.

A_k is a constant which converts from MeV/gm to units of dose (usually rads).

Appendix

$D_e(z)$ is the surface or skin dose in rads which would be delivered to a slab of material adjacent to the aluminum slab. The derivation of equation (A1) is given in the text.

BEDOSE also calculates the transmitted flux $N_e(Z)$ given by

$$N_e(z) = \int_{E_{min}}^{E_{max}} \Phi(E)\ T_N(E,x)dE. \qquad (A2)$$

$T_N(E,x)$ is the fraction of incident electrons with energy between E and E+dE, $\Phi(E)dE$, that are transmitted through a reduced thickness, x.

$N_e(Z)$ is the total number of electrons per cm^2 penetrating the slab, and $\frac{D_e(z)}{A_k N_e(z)}$ is equal to $\left\langle \frac{dE'}{dz} \right\rangle$, the average energy deposition per unit depth produced by the transmitted electrons in the irradiated material.

The bremsstrahlung dose is calculated from the equation

$$D_b(z) = A_k \langle \sigma_a \rangle Z(10^{-4}) \int_{E_{min}}^{E_{max}} E^2\ \Phi(E)a(z,E)dE, \qquad (A3)$$

the derivation of which is given in the text. Z is the atomic number of the shielding material, a(z,E) is the coefficient in the forward bremsstrahlung efficiency formula (determined from Monte Carlo calculations), and $\langle \sigma_a \rangle$ is the average mass absorption coefficient of the irradiated material for the incident bremsstrahlung energy spectrum.

The quantities $\Phi(E)$, $T_E(E,x)$, $T_N(E,x)$, z, and A_k are given as input, while the quantities $R_o(E)$, $R'_o(E)$, $\langle \sigma_a \rangle$, Z, and a(z,E) are fixed in the code. $\Phi(E)$ can either be specified explicitly at various energies and the code will assume exponential behavior in between, or it can be specified

by the analytic form $A_o e^{-FE-GE^2}$ (E in MeV). T_E and T_N are specified by analytic fits of the form, $Ae^{-(Bx+Cx^2+Dx^3)}$, to the Monte Carlo transmission calculations. E_{min} for the electron dose is determined by the requirement that $x \leq CTF$, where CTF is specified in the input. E_{min} for the bremsstrahlung dose is fixed in the code at a value of $(\frac{Z}{32})^{0.6}$.

II. INPUT FORMAT

The input quantities, their meaning, and the input format are listed in the table below.

Appendix

TABLE AI

INPUT INFORMATION

Card Number	Item(s)	Format	Purpose
1	CTF	E14.7	T_N and T_E set equal to zero for x> CTF.
2*	A_0,F,G	3E14.7	$\Phi(E)= A_0 e^{-FE-GE^2}$ if analytic form is specified for flux.
3	$\Delta z, z_{min}, z_{max}$	3E14.7	Code will compute doses for slab thickness equal to $z_{min}, z_{min}+\Delta z, \cdots z_{max}$.
4	N	I5	Number of energy region cards to follow.
5a,5b,etc.	E_i, n_i	E14.7,I5	The $\int_0^{E_{max}}$ is divided into N regions. The number of steps in the integration from E_{i-1} to E_i is equal to n_i; $E_{max}=E_N$, $E_0=0$. Maximum number of entries = 20.
6	A_k	E14.7	Converts MeV/gm to units of dose. $A_k = 1.6 \times 10^{8}$ for rads.
7	A,B,C,D	4E14.7	Coefficients for $T_N(x)=Ae^{-(Bx+Cx^2+Dx^3)}$
8	A_1, B_1, C_1, D_1	4E14.7	Coefficients for $T_E(x)=A_1 e^{-(B_1 x+C_1 x^2+D_1 x^3)}$

TABLE A1 CONT'D

INPUT INFORMATION

Card Number	Item(s)	Format	Purpose
9	IFLX, IDE Control Sentinels	2I5	If IDE = 1, code will edit after every E_i given on cards 5a, 5b, etc. If IDE = 0, code will edit at end of calculation. If IFLX = 0, $\Phi(E)$ is to be specified by input table. If IFLX = 1, $\Phi(E)$ given in analytic form on card 2.
10**	KMAX	I5	Number of flux cards to follow.
11a, 11b, etc** (KMAX cards)	$E_k, \Phi(E_k)$ K = (1,KMAX)	2E14.8	Specifies $\Phi(E)$ at energy E_k. Code interpolates logarithmically from E_{k-1} to E_k. E_1 = 0. Maximum number of entries = 40.

*This card must be in deck, but is ignored if IFLX = 0

**Must not be used if IFLX = 1

Total number of Input Cards = 8+N (if IFLX = 1)
9+N+KMAX (if IFLX = 0)

Appendix

III. OUTPUT FORMAT

The output consists of two parts; a section containing the input information and a section containing the code output. The input information is clearly labeled and is given in the following order:

1. The scale factor, A_k.
2. The integration edit intervals and number of integration steps, E_i and n_i.
3. A_1, B_1, C_1, D_1
4. A, B, C, D.
5. CTF, A_0, F, G.
6. The flux energy spectrum, if given, E_k and $\Phi(E_k)$.
7. $\int_0^\infty \Phi(E)\, dE$ which is labeled normalization.

The code output information is listed in 5 columns. Column 1 labeled, Z, is the slab thickness in gm/cm^2. Column 2 labeled, Electron Dose, is the skin dose in whatever units are used for A_k (usually rads). If IDE = 1, the code will print accumulated dose after every $E_i (i = 1,N)$ given in the input deck. With this option, the user can determine which regions of the electron energy spectrum are contributing to the dose. Column 3, labeled Electron Number, gives the number of electrons penetrating the slab per cm^2. The same option applies for IDE = 1. Column 4 labeled, E, (DE/DX), gives E_i when IDE = 1, except for the last entry which is $\left\langle \frac{dE'}{dz} \right\rangle$ the average energy deposition per gm/cm^2 for the electrons that penetrate the slab. When IDE = 0 only $\left\langle \frac{dE'}{dz} \right\rangle$ is given in this column.

Column 5 labeled, Brem Dose, is the bremsstrahlung dose produced by the electron bremsstrhalung. The units are the same as the electron dose. The option IDE = 1 again produces an edit after every E_i.

IV. ADDITIONAL COMMENTS

1. The code calculates radiation dose in a slab of material behind an aluminum slab shield. Care must be taken in applying the results to other materials and spacecraft geometries (see text).

2. The transmission coefficients are energy independent in the present version of the code. Use a transmission curve for an incident energy close to that which contributes most to the dose.

3. The angular distribution of the incident flux need not be isotropic, but the transmission curves should be determined for whatever angular distribution is assumed for the flux.

4. If E_{MAX} is higher than E_{KMAX}, the code will exponentially extrapolate $\Phi(E)$ out to E_{MAX}. The slope will be the same as the slope from E_{KMAX-1} to E_{KMAX}.

5. The $R'_0(E)$ presently in the code is for muscle.

6. Generation time + Running time = 6 seconds on Univac 1108 for five slab thicknesses and 200 integration points per slab.

7. A listing with sample output follows below.

```
*       HDG     BREMSSTRAHLUNG-ELECTRON DOSE (INGLEY/BELLCOMM)
*IT     FOR     BEDOSE,BEDOSE
        DIMENSION EE(40),EL(40),ENB(20),INB(20)
       IWR=6
       IRE=5
       READ (IRE,25)CTE,A0,E,G
       READ (IRE,101)DZ,ZERT,ZMAX
        M=0
        N=(ZMAX-ZERT)/DZ+1
       READ (IRE,700)NUB,(ENB(I),INB(I),I=1,NUB)
       READ (IRE,29)AK,A,B,C,D,A1,B1,C1,D1
       WRITE(IWR,20)AK,(ENB(I),INB(I),I=1,NUB)
       WRITE(IWR,21)A1,B1,C1,D1
       WRITE(IWR,3)A,B,C,D
       WRITE(IWR,23)CTE,A0,E,G
        READ(IRE,30)IFLX,IDE
        IF(IFLX-1)1,31,31
1      READ (IRE,2)KMAX,(EE(K),EL(K),K=1,KMAX)
       WRITE (IWR,708)
       IF (EE(KMAX)-ENB(NUB))2000,2001,2001
2000   KMAX=KMAX+1
       EE(KMAX)=ENB(NUB)
       EL(KMAX)=EXP(ALOG(EL(KMAX-1))+(EE(KMAX)-EE(KMAX-1))/(EE(KMAX-1)-EE
      1(KMAX-2))*(ALOG(EL(KMAX-1)/EL(KMAX-2))))
2001   DO 5 K=1,KMAX
       WRITE (IWR,1000)EE(K),EL(K)
5      EL(K)=ALOG(EL(K))
       K=1
       SUM3=0.
100    SUM3=SUM3+(EXP (EL(K+1))-EXP (EL(K)))/((EL(K+1)-EL(K))/(EE(K+1)-EE
      1(K)))
       K=K+1
       IF (K-KMAX)100,110,110
 31     DE=ENB(NUB)/200.
        SUM3=0.
        EN=DE*.5
        DO 32 IA=1,200
        SUM3=SUM3+A0*DE*EXP(-(E*EN+G*EN**2))
 32     EN=EN+DE
110    WRITE (IWR,800)SUM3
       WRITE (IWR,4)
       Z=ZERT
       DO 6 J=1,N
       SUM1=0.
       SUM2=0.
        SUM4=0.
       K=1
        EMIN=(Z/32.)**.6
        EMIN2=SQRT((CTE*Z)*(CTE*Z+.2378)/(.4364-.0128*CTE*Z))
       L=1
704    IF (EMIN-ENB(L))701,702,703
703    IF (L-NUB)705,600,1
705    L=L+1
       GO TO 704
702    IF (L-NUB)706,600,1
```

```
706     L=L+1
701     FL=EMIN
        DO 707 KA=L,NUB
        AIB=INB(KA)
        DE=(ENB(KA)-EL)/AIB
         EN=EL-DE
         NEA=INP(KA)+1
300     DO 7 I=1,NEA
        EN=EN+DE
        R=SQRT(.4379*EN**2+.01415)-.1180-.0064*EN**2
         R1=0.7*R
        X=Z/R
         DN=0.
         DP=0.
         IF(X-.6)16,17,17
 16      ABREM=24.3*(X**1.13)*EXP(-1.18*X)
         GO TO 18
 17      ABREM=4.4*EXP(-(.125*(EN**.321)*(X-.6)/R))
 18      IF(EN-EMIN2)11,51,51
 51     DN=A*EXP(-(B*X+C*X**2+D*X**3))
        DP=A1*(B1+2.*C1*X+3.*D1*X**2)*EXP (-(B1*X+C1*X**2+D1*X**3))/R1
 11      IF(IFLX-1)33,34,34
 33      IF(EN-EF(K))8,9,10
10      K=K+1
        IF (K-KMAX)11,11,12
12      K=KMAX
9       FU=EXP (FL(K))
        GO TO 13
8       IF (K-1)1,9,14
14      FU=EXP ((EN-EF(K-1))*(FL(K)-FL(K-1))/(EF(K)-EF(K-1))+FL(K-1))
         GO TO 13
 34      FU=A0*EXP(-(F*EN+G*EN**2))
 13      IF(I-1)40,40,41
 40      SIMPC=1.
         GO TO 46
 41      IF(M-1)42,43,43
 42      SIMPC=4.
         M=3
         GO TO 44
 43      SIMPC=2.
         M=0
 44      IF(I-NEA)46,45,45
 45      SIMPC=1.
         M=0
 46      SUM1=SUM1+FU*DP*EN*DE*SIMPC/3.
         SUM2=SUM2+FU*DN*SIMPC*DE/3.
 7       SUM4=SUM4+FU*ABREM*(EN**2)*SIMPC*DE/3.
         EL=ENB(KA)
         IF(IDE-1)707,35,35
 35      SUM1P=SUM1*AK
         SUM4P=SUM4*AK*(4.03E-05)
         WRITE(IWR,15)Z,SUM1P,SUM2,EL,SUM4P
707     EL=ENB(KA)
 600     DEDX=SUM1/SUM2
        SUM1=SUM1*AK
```

```
      SUM4=SUM4*AK*(4.03E-05)
      WRITE(IWR,36)Z,SUM1,SUM2,DEDX,SUM4
6     Z=Z+DZ
      WRITE(IWR,37)
      CALL EXIT
2     FORMAT (I5/(2E14.8))
    3 FORMAT(3H A=E14.7/3H B=E14.7/3H C=E14.7/3H D=E14.7)
 4    FORMAT(//75H   Z (GM/CM2)  ELECTRON DOSE  ELECTRON NUMBER   E,(DE
     1/DX)       BREM DOSE    )
 15   FORMAT(5E15.6)
20    FORMAT(22H INTEGRATION CONSTANT=E14.7/18H INTEGRATION STEPS/
     110X,6HENERGY,7X,12HNO. OF STEPS/(E20.7,I10))
   21 FORMAT(  //4H A1=E14.7/4H B1=E14.7/4H C1=E14.7/4H D1=E14.7)
23    FORMAT(5H CTE=E14.7/4H A0=E14.7/3H F=E14.7/3H G=E14.7)
25    FORMAT(E14.7/(3F14.7))
29    FORMAT(F14.7/(4F14.7))
 30    FORMAT(2I5)
 36    FORMAT(/5E15.6/)
 37    FORMAT(17H PROBLEM FINISHED)
  101 FORMAT(3F14.8)
700   FORMAT (I5,/(E14.7,I5))
708   FORMAT (//9H SPECTRUM/10X,6HENERGY,15X,4HFLUX)
  800 FORMAT(15H NORMALIZATION=E14.7)
1000  FORMAT (2E20.7)
      END
```

```
'       XQT      BEDOSE
1.0
         7.1E12.575              .055
        .5          .5          2.5
   10
.5                   50
1.                   50
1.5                  25
2.                   25
3.                   20
4.                   10
5.                   10
6.                   10
7.                   10
8.                   10
        1.6-08
1.072           2.80            -6.237                  11.96
1.058           3.99            -4.66           11.1
    0    1
    6
0.                      4.67E11
1.5                      3.27E6
2.                       2.36E6
3.                       1.65E6
7.                       5.45E5
20.                       3.5E4
```

INTEGRATION CONSTANT= .1600000-07

INTEGRATION STEPS

ENERGY	NO. OF STEPS
.5000000-00	50
.1000000+01	50
.1500000+01	25
.2000000+01	25
.3000000+01	20
.4000000+01	10
.5000000+01	10
.6000000+01	10
.7000000+01	10
.8000000+01	10

A1= .1058000+01
B1= .3990000+01
C1= -.4660000+01
D1= .1110000+02
A= .1072000+01
B= .2800000+01
C= -.6237000+01
D= .1196000+02
CTF= .1000000+01
A0= .7100000+13
F= .5750000-00
G= .5500000-01

SPECTRUM

ENERGY	FLUX
.0000000	.4670000+12
.1500000+01	.3270000+07
.2000000+01	.2360000+07
.3000000+01	.1650000+07
.7000000+01	.5450000+06
.2000000+02	.3500000+05

NORMALIZATION= .5902720+11

Z (GM/CM2)	ELECTRON DOSE	ELECTRON NUMBER	E,(DE/DX)	BREM DOSE
.500000-00	.000000	.000000	.500000-00	.469378-03
.500000-00	.199939-02	.117874+05	.100000+01	.133649-02
.500000-00	.655573-01	.439178+06	.150000+01	.140944-02
.500000-00	.113535+00	.838160+06	.200000+01	.142576-02
.500000-00	.219298-00	.188101+07	.300000+01	.146307-02
.500000-00	.310604-00	.284046+07	.400000+01	.150366-02
.500000-00	.388246-00	.364168+07	.500000+01	.154443-02
.500000-00	.453066-00	.428515+07	.600000+01	.158286-02
.500000-00	.506350-00	.479290+07	.700000+01	.161768-02
.500000-00	.550996-00	.520230+07	.800000+01	.164942-02
.500000-00	.550996-00	.520230+07	.661963+01	.164942-02
.100000+01	.000000	.000000	.500000-00	.110476-03
.100000+01	.000000	.000000	.100000+01	.627776-03
.100000+01	.000000	.000000	.150000+01	.689093-03
.100000+01	.225989-03	.147084+04	.200000+01	.700287-03

.100000+01	.213311-01	.160919+06	.300000+01	.739172-03
.100000+01	.736830-01	.618725+06	.400000+01	.806350-03
.100000+01	.128354-00	.115151+07	.500000+01	.878173-03
.100000+01	.175398-00	.163507+07	.600000+01	.948569-03
.100000+01	.214094-00	.203906+07	.700000+01	.101409-02
.100000+01	.246510-00	.237547+07	.800000+01	.107498-02
.100000+01	.246510-00	.237547+07	.648583+01	.107498-02
.150000+01	.000000	.000000	.500000-00	.311317-04
.150000+01	.000000	.000000	.100000+01	.351317-03
.150000+01	.000000	.000000	.150000+01	.403329-03
.150000+01	.000000	.000000	.200000+01	.413749-03
.150000+01	.360002-03	.240767+04	.300000+01	.447009-03
.150000+01	.105547-01	.772421+05	.400000+01	.496300-03
.150000+01	.379631-01	.299978+06	.500000+01	.582595-03
.150000+01	.710424-01	.594559+06	.600000+01	.675771-03
.150000+01	.101665+00	.885831+06	.700000+01	.764834-03
.150000+01	.128339-00	.115007+07	.800000+01	.849218-03
.150000+01	.128339-00	.115007+07	.697449+01	.849218-03
.200000+01	.000000	.000000	.500000-00	.954008-05
.200000+01	.000000	.000000	.100000+01	.214400-03
.200000+01	.000000	.000000	.150000+01	.258559-03
.200000+01	.000000	.000000	.200000+01	.268259-03
.200000+01	.000000	.000000	.300000+01	.300297-03
.200000+01	.398422-03	.268554+04	.400000+01	.348573-03
.200000+01	.608672-02	.436243+05	.500000+01	.410339-03
.200000+01	.209747-01	.159032+06	.600000+01	.496514-03
.200000+01	.406683-01	.323069+06	.700000+01	.602496-03
.200000+01	.609687-01	.502664+06	.800000+01	.704877-03
.200000+01	.609687-01	.502664+06	.758070+01	.704877-03
.250000+01	.000000	.000000	.500000-00	.307123-05
.250000+01	.000000	.000000	.100000+01	.137996-03
.250000+01	.000000	.000000	.150000+01	.175521-03
.250000+01	.000000	.000000	.200000+01	.184553-03
.250000+01	.000000	.000000	.300000+01	.215416-03
.250000+01	.000000	.000000	.400000+01	.262697-03
.250000+01	.384402-03	.258912+04	.500000+01	.323628-03
.250000+01	.375916-02	.264857+05	.600000+01	.393615-03
.250000+01	.121411-01	.892640+05	.700000+01	.469642-03
.250000+01	.242375-01	.185134+06	.818243+01	.585124-03

PROBLEM FINISHED

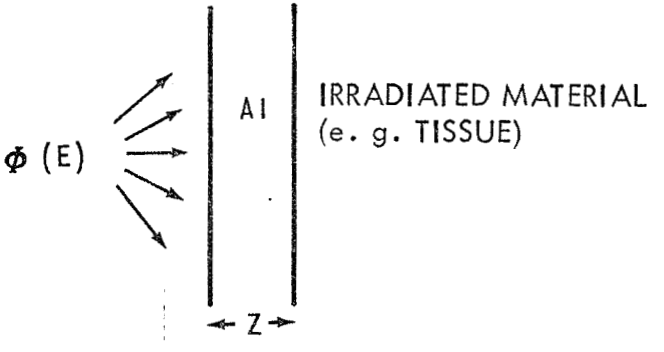

FIGURE I - ELECTRON DOSE MODEL

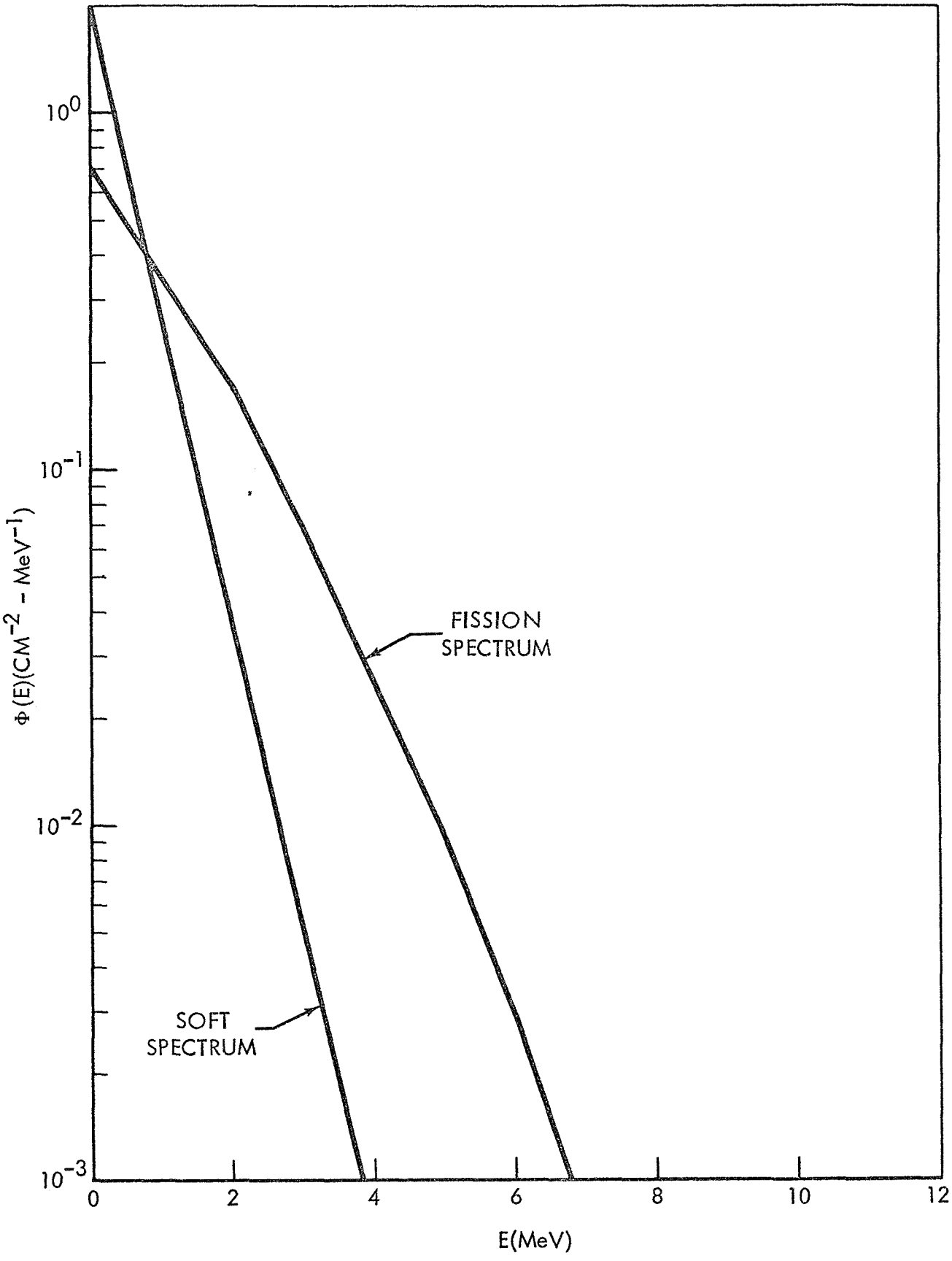

FIGURE 1a - MODEL ELECTRON SPECTRA FOR RADIATION DOSE CALCULATIONS

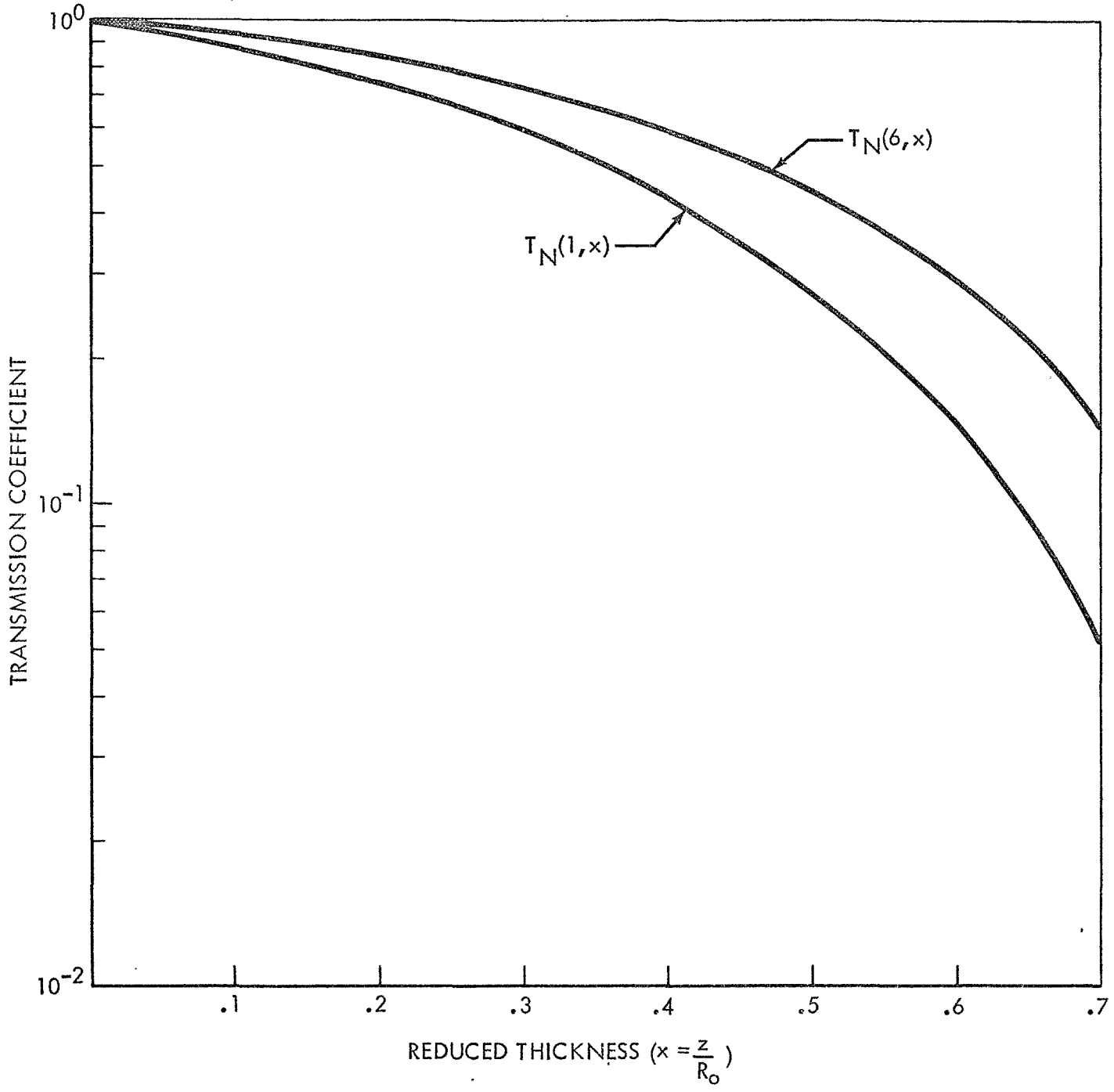

FIGURE 2 - NUMBER TRANSMISSION COEFFICIENT vs REDUCED THICKNESS FOR INCIDENT ELECTRON ENERGIES OF 1 AND 6 MeV

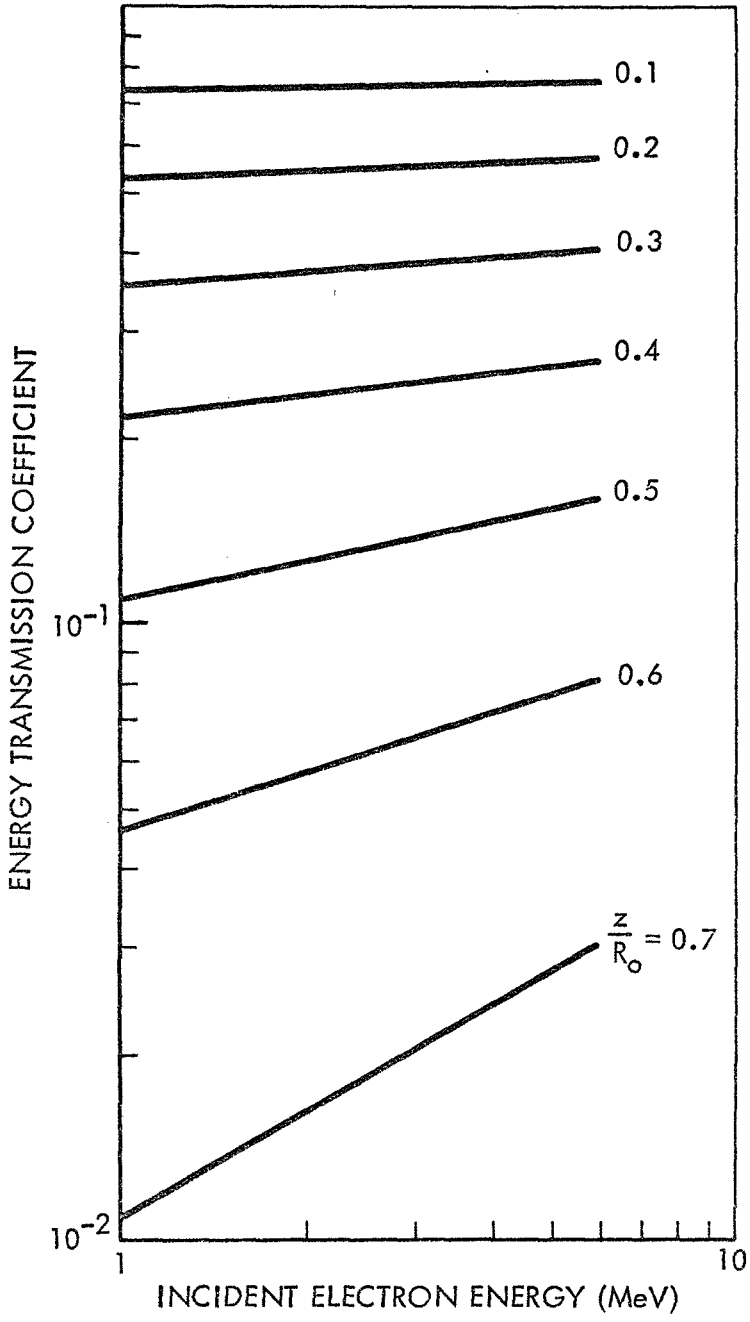

FIGURE 3a - VARIATION OF ENERGY TRANSMISSION COEFFICIENT WITH INCIDENT ELECTRON ENERGY

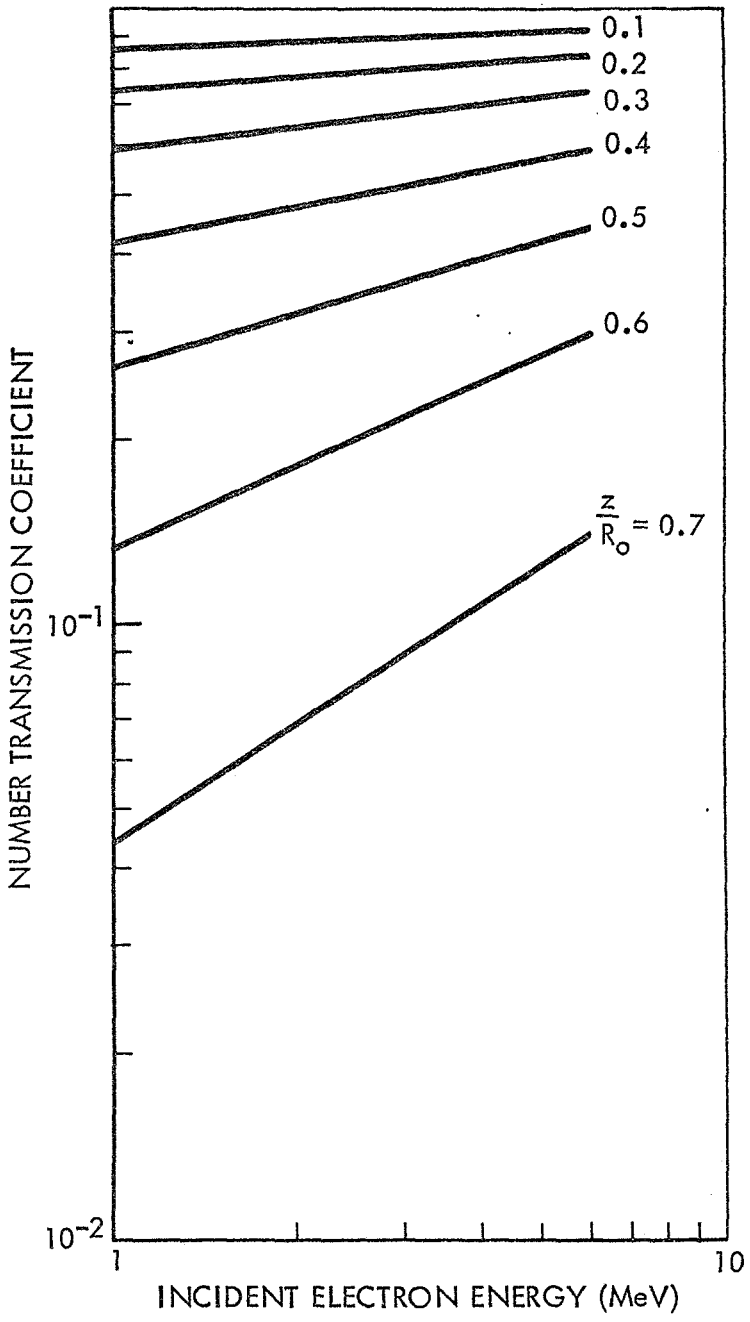

FIGURE 3b - VARIATION OF NUMBER TRANSMISSION COEFFICIENT WITH INCIDENT ELECTRON ENERGY

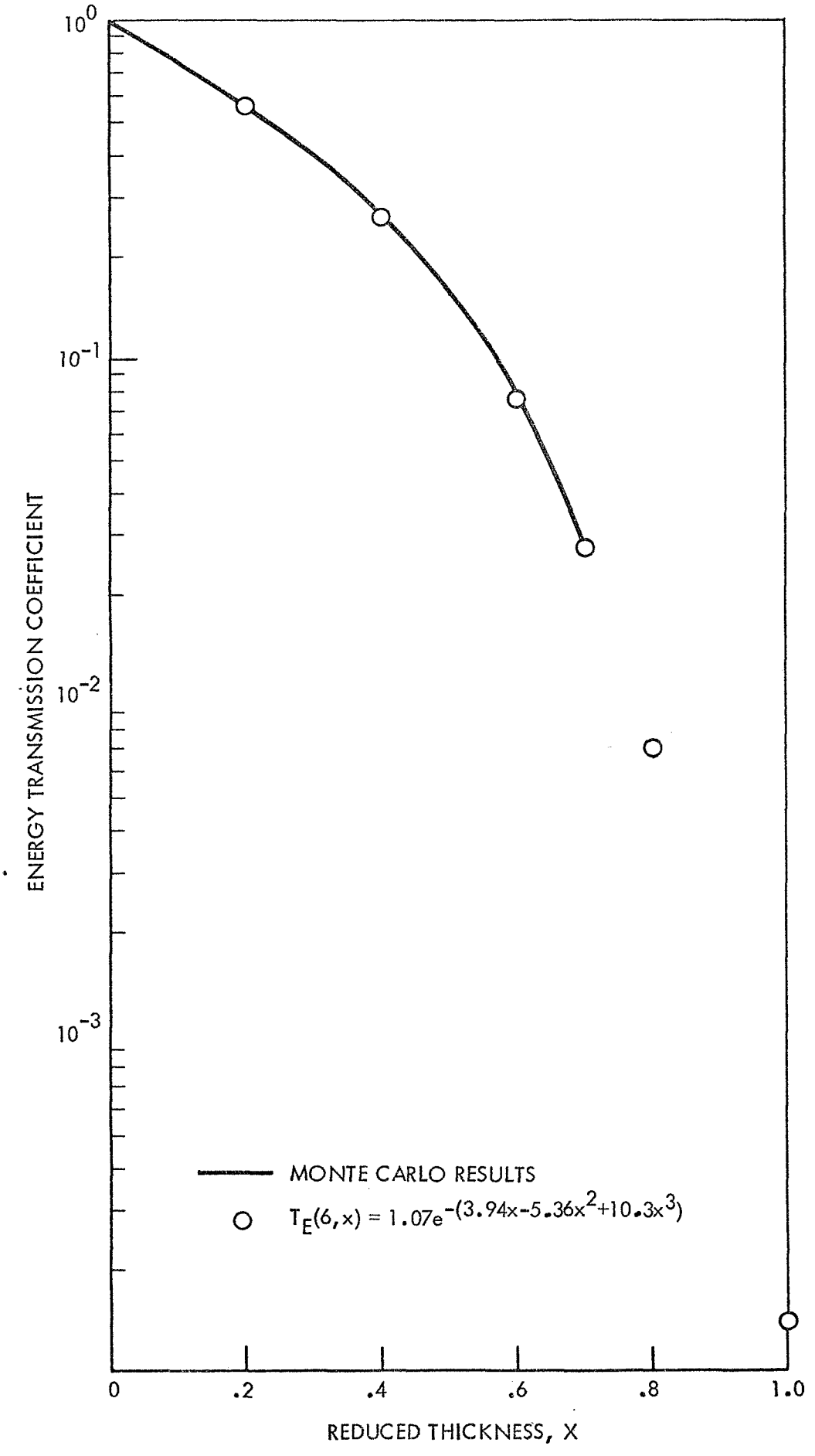

FIGURE 4 - ANALYTIC FIT TO MONTE CARLO CALCULATIONS FOR $T_E(6,x)$.

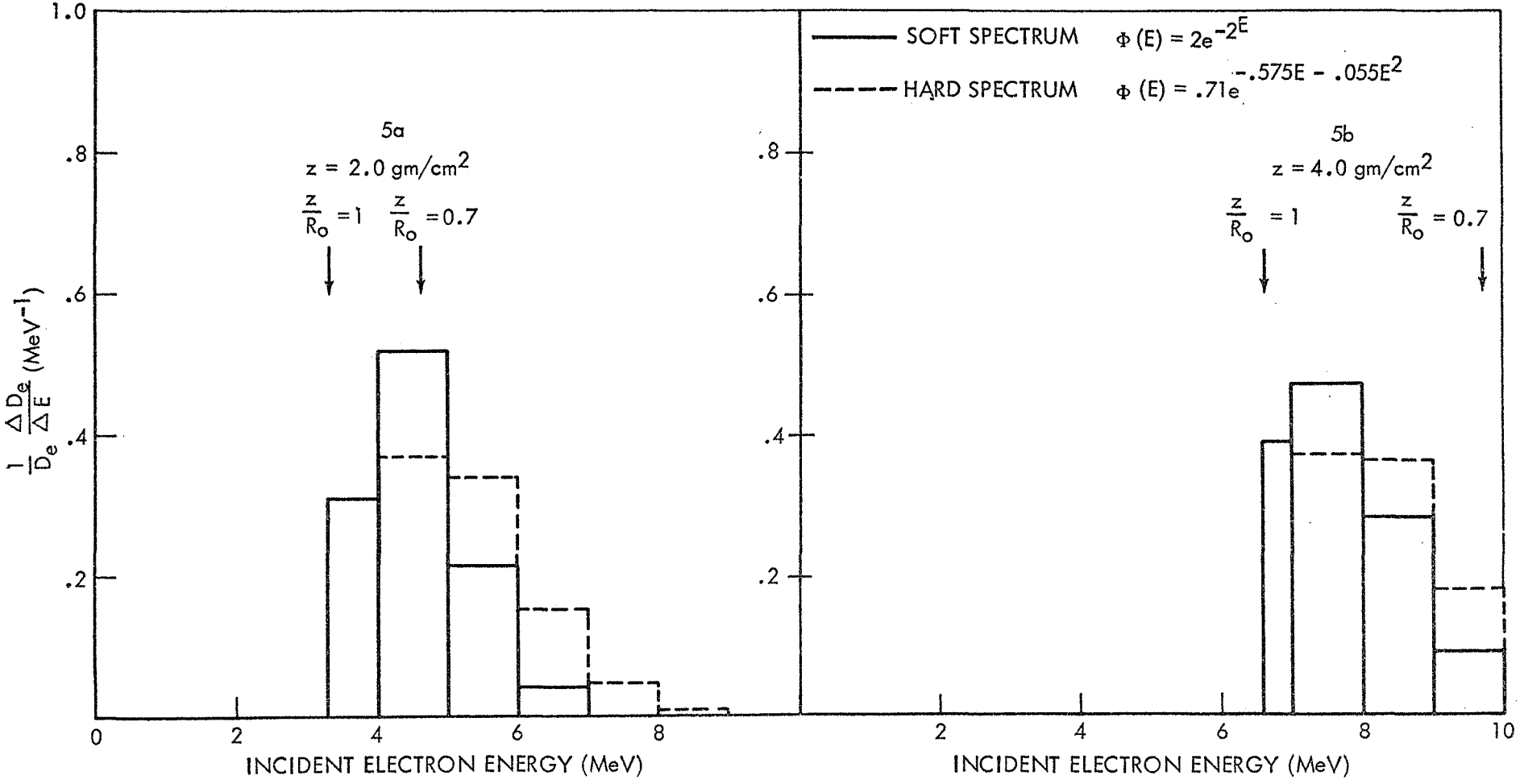

FIGURE 5a & 5b - CONTRIBUTIONS TO ELECTRON DOSE AS A FUNCTION OF ENERGY FOR HARD AND SOFT ELECTRON SPECTRA

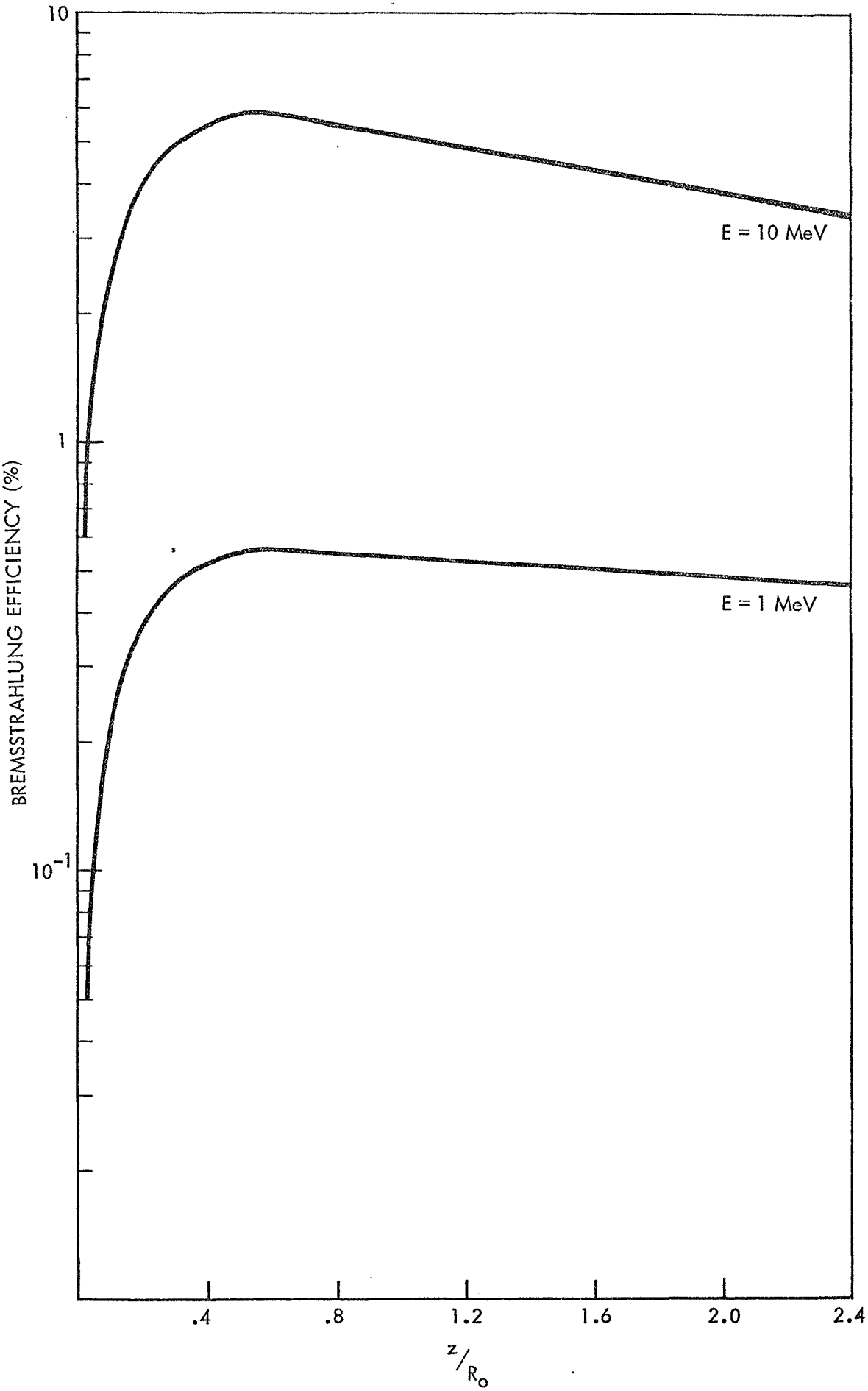

FIGURE 6 - BREMSSTRAHLUNG EFFICIENCY vs REDUCED THICKNESS AT 1 AND 10 MeV

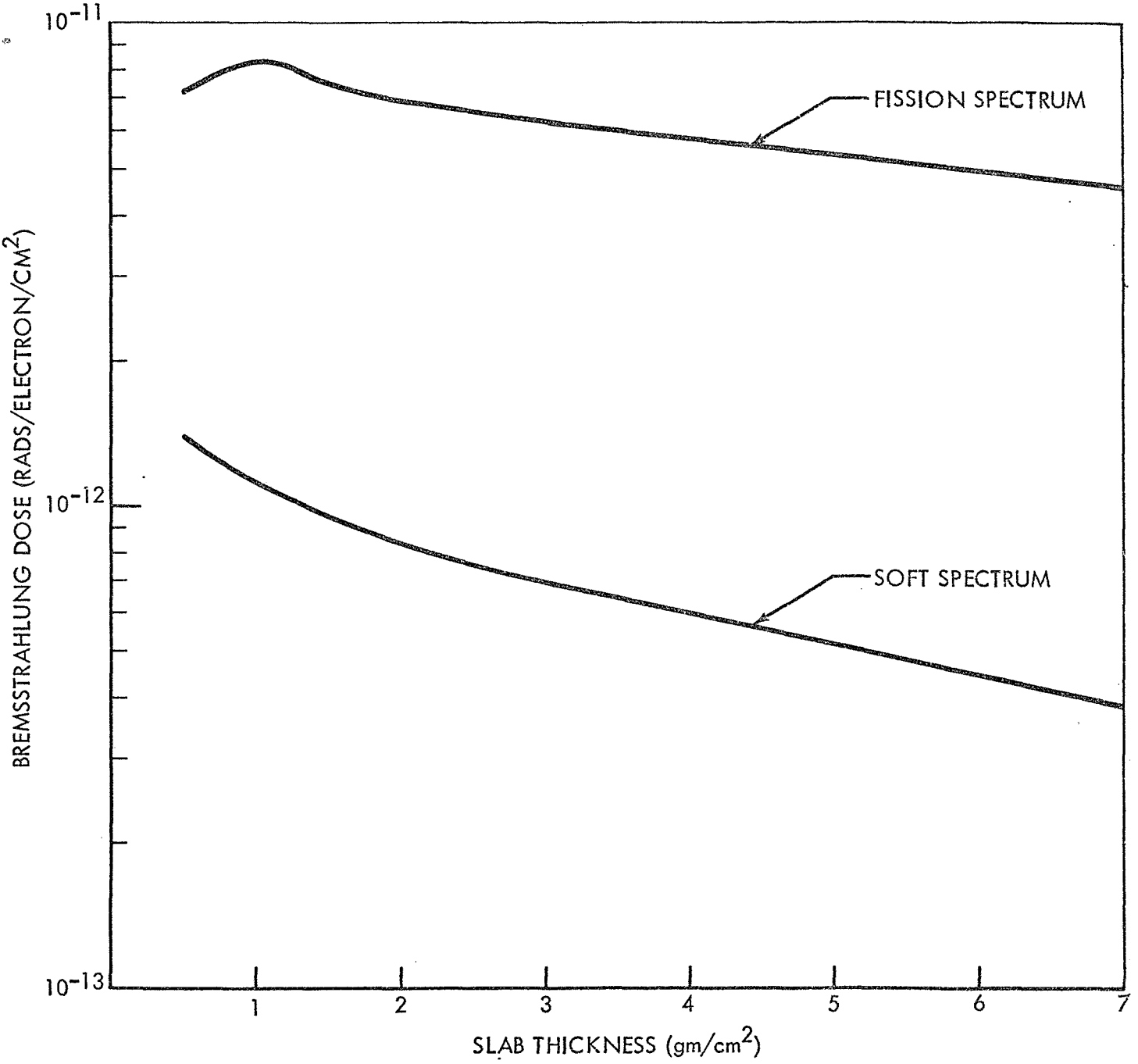

FIGURE 7 - BREMSSTRAHLUNG DOSE vs SLAB THICKNESS FOR ALUMINUM SLABS

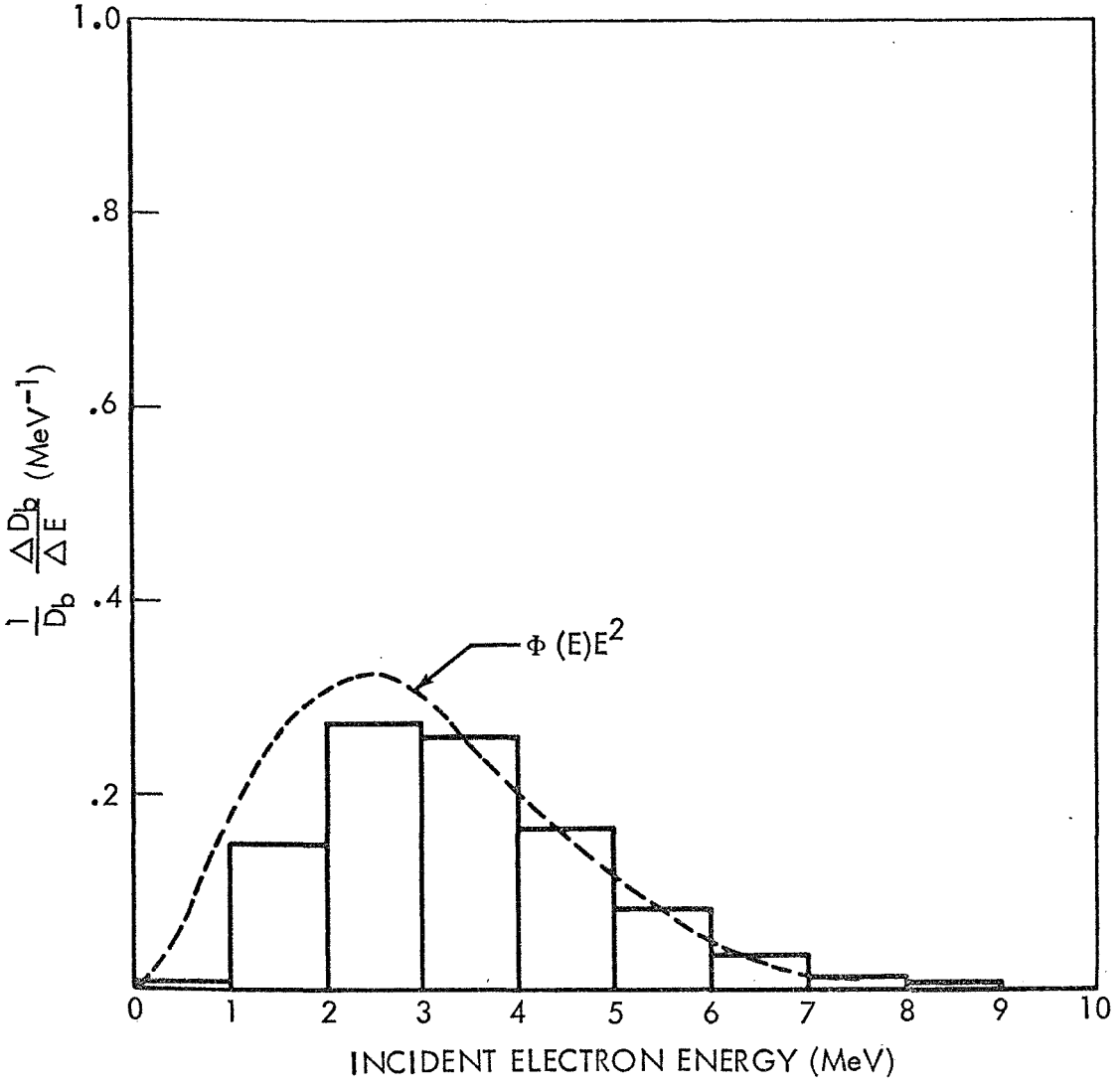

FIGURE 8 - ENERGY CONTRIBUTIONS TO BREMSTRAHLUNG DOSE

$z = 4.0$ gm/cm^2

FISSION ELECTRON SPECTRUM

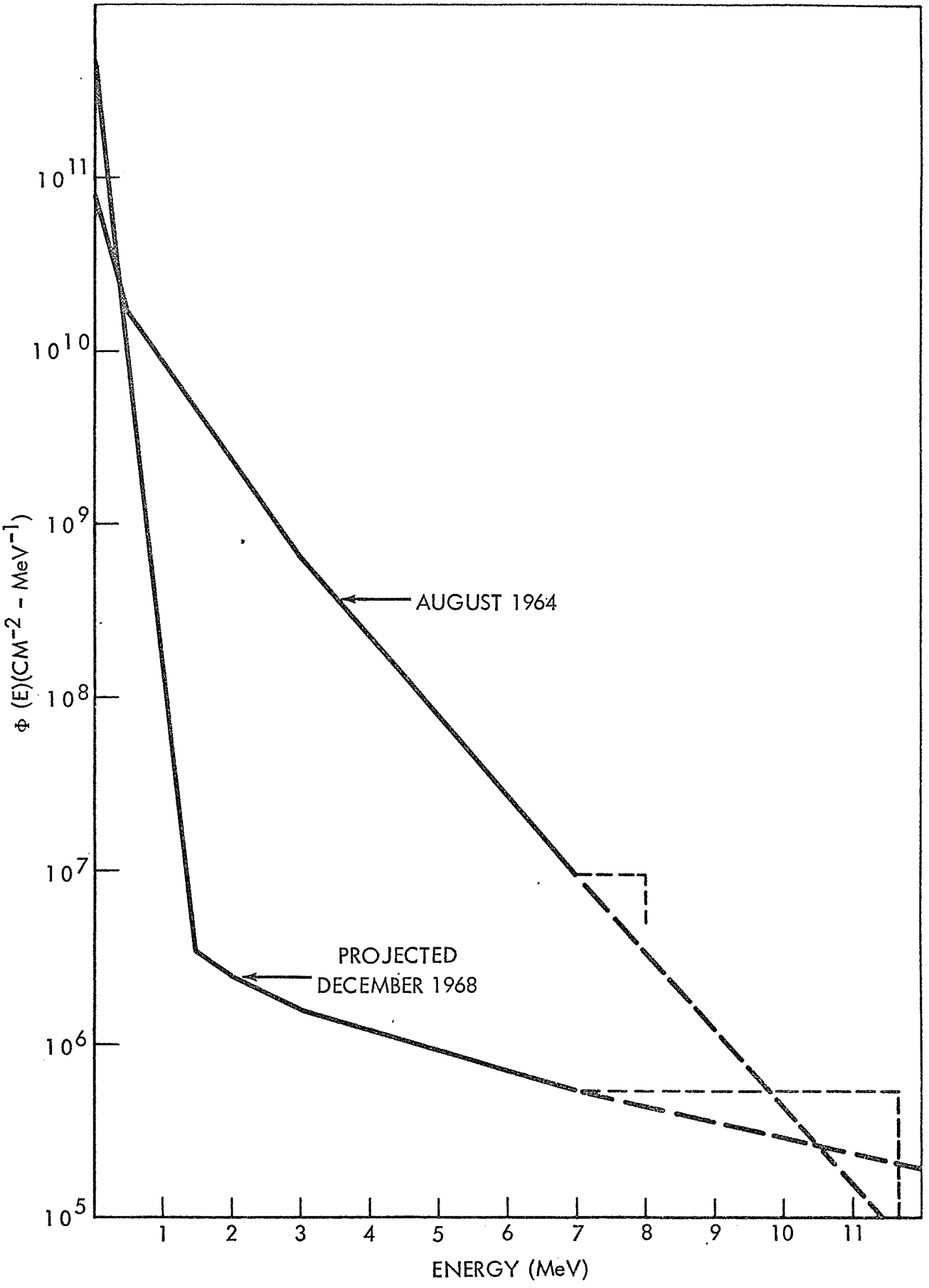

FIGURE 9 - MODEL AE2 ELECTRON SPECTRA FOR 300 NM -30°
INCLINATION CIRCULAR ORBIT

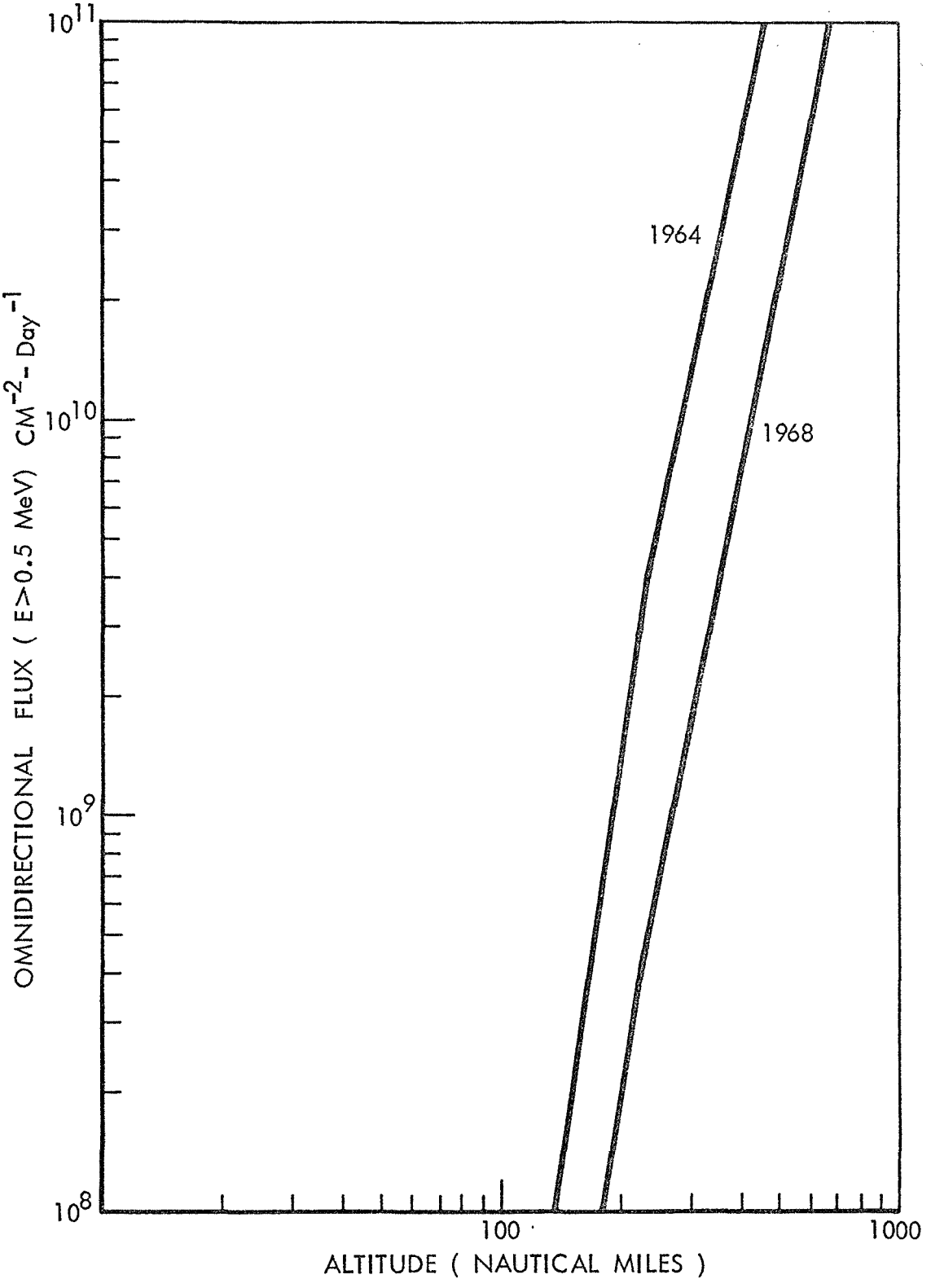

FIGURE 10 - OMNIDIRECTIONAL ELECTRON FLUX VS. ALTITUDE FOR CIRCULAR ORBITS AT 30° INCLINATION

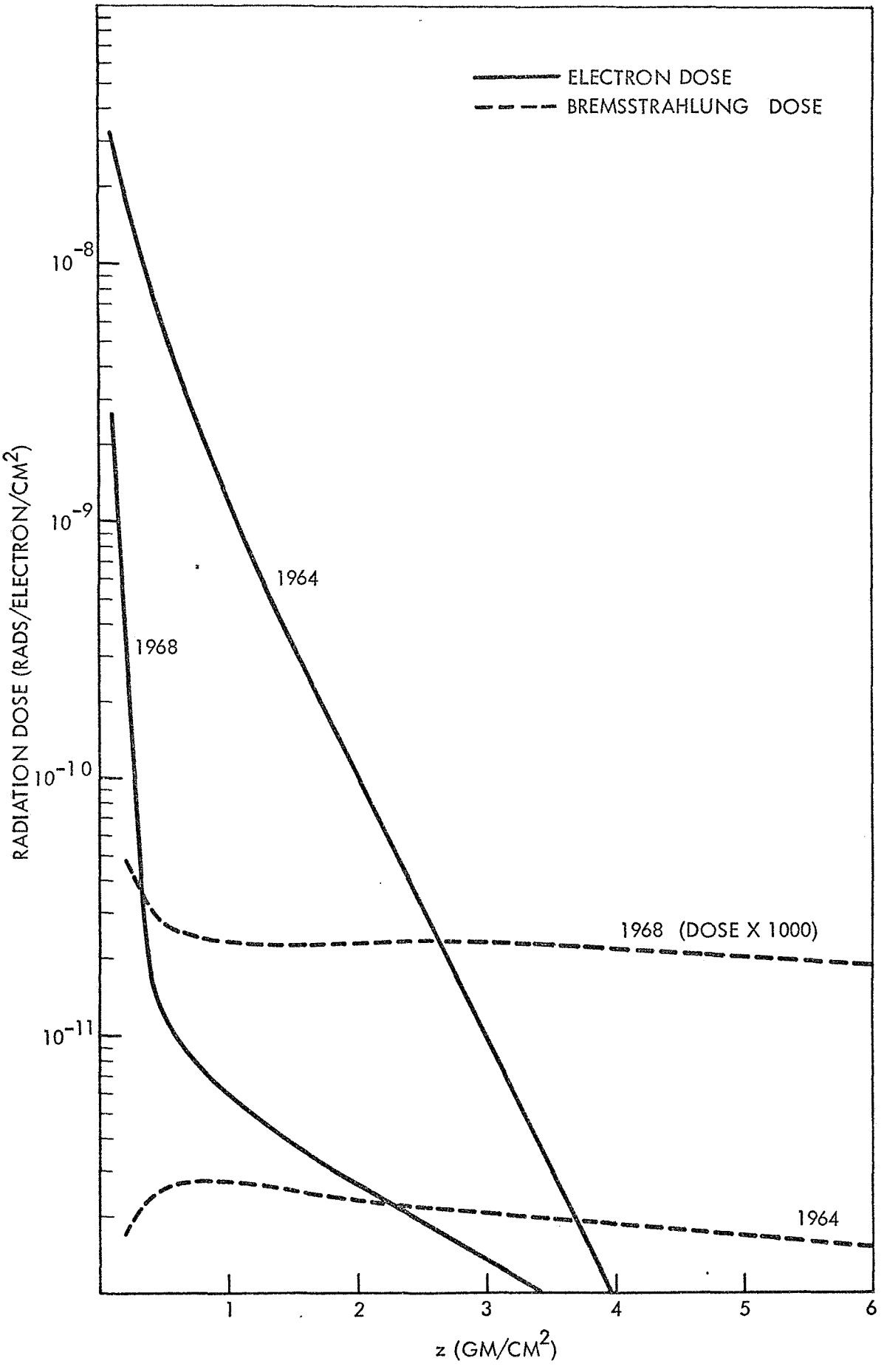

FIGURE 11 - NORMALIZED ELECTRON AND BREMSSTRAHLUNG DOSES FOR AE2 MODEL SPECTRA vs SLAB THICKNESS.

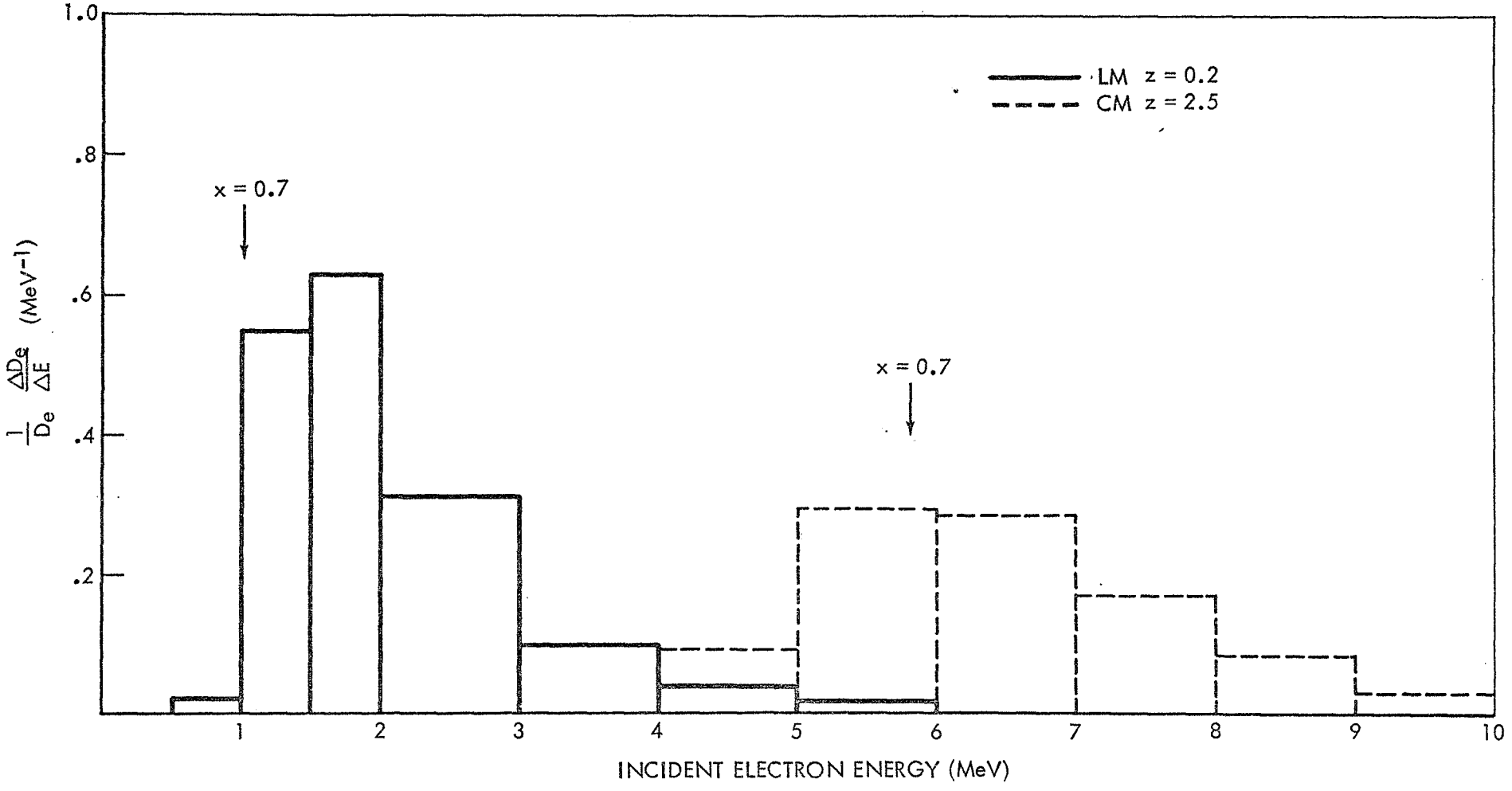

FIGURE 12 - ENERGY CONTRIBUTION TO DOSE FOR 1964 SPECTRUM

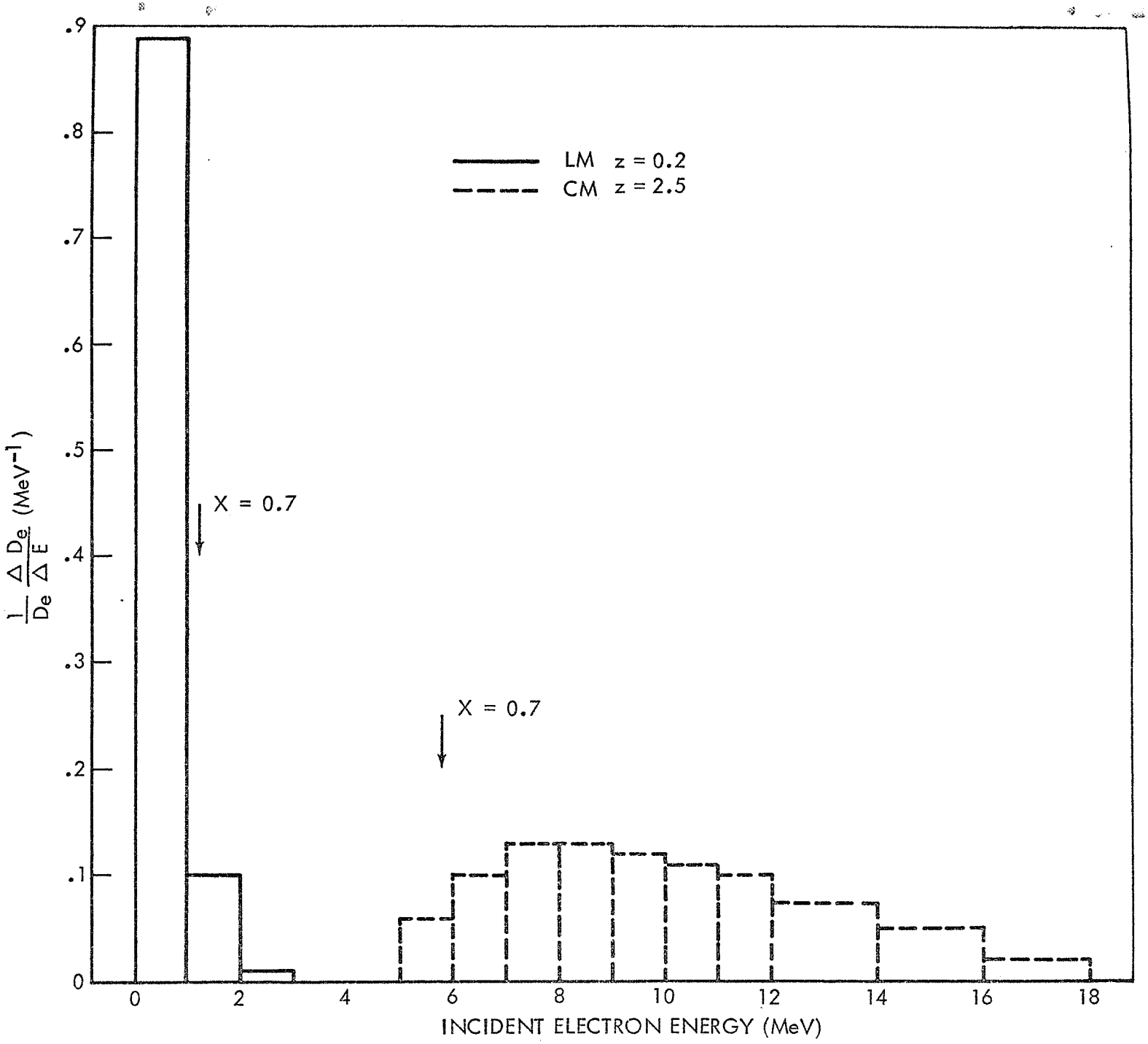

FIGURE 13 - ENERGY CONTRIBUTION TO DOSE FOR 1968 SPECTRUM